NASA Technical Memorandum 78978

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(NASA-TM-78978) EFFECTS OF MOISTURE PROFILES AND LAMINATE CONFIGURATION ON THE HYGRO STRESSES IN ADVANCED COMPOSITES (NASA) 16 p HC A02/MF A01 CSCL 11D

N78-32191

Unclas
G3/24 33635

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TECHNICAL PAPER to be presented at the
Tenth National Technical Conference
sponsored by the Society for the Advancement
of Material and Process Engineering
Kiameshe Lake, New York, October 17-19, 1978

E-9755

EFFECTS OF MOISTURE PROFILES AND LAMINATE CONFIGURATION ON THE HYGRO STRESSES IN ADVANCED COMPOSITES

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Abstract

A computational investigation was performed using a recently developed integrated hygrothermomechanical theory to predict the effects of three moisture profiles on the ply hygro stresses in angleplied laminates. The moisture profiles were linear, parabolic and hyperbolic. Moisture content varied from 1 percent in the exposed ply to zero in the protected ply. The angleplied laminates were of two generic configurations, $[(\pm\theta)_2]_s$ and $[\theta/0/-\theta/0]_s$, with $0 \leq \theta \leq 90^{\circ}$. The results obtained are summarized graphically to illustrate the effects of both moisture profile and laminate configuration. The results indicate that ply transverse tensile hygro stresses may reach sufficiently high magnitudes to cause transply cracking.

1.0 INTRODUCTION

Moisture in advanced fiber composites and its degradation effects on the mechanical properties of these composites have received extensive attention in the composites community as is evident from the works cited in ref. 1. An integrated theory to predict the hygrothermomechanical response of advanced composite structural components is described in ref. 1. Briefly, this theory determines the hygrothermomechanical response by integrating composite micromechanics, composite macromechanics, combined-stress failure criteria, laminate theory and advanced structural mechanics. The details and verification of the theory with experimental data are described in ref. 1. This integrated theory is used to predict the effects of different moisture profiles and laminate configurations on ply hygro stresses and continues the work reported in ref. 1.

The moisture profiles considered are linear, parabolic and hyperbolic varying from 1 percent in the ply at the exposed surface (exposed ply) to zero in the ply at the protected surface (protected ply). Greater than 1 percent moisture content in the exposed ply is considered unlikely for composites exposed to ambient con-

ditions. The composite laminates were assumed to be made from AS/E (intermediate modulus graphite fiber in an epoxy matrix) with two generic angleplied laminate configuration $[(\pm\theta)_2]_s$ and $[\theta/0/-\theta/0]_s$ with $0 \le \theta \le 90^o$. The hygro stresses in the plies were computed in each angleplied laminate for each of the moisture profiles. Schematics of the three moisture profiles and ply configurations are shown in figure 1. Note that at $\theta = 0$ or 90^o the $[(\pm\theta)_2]_s$ laminate and at $\theta = 0$ the $[\theta/0/-\theta/0]_s$ laminate correspond to a unidirectional composite (UDC). At $\theta = 45^o$ the $[(\pm\theta)_2]_s$ and $\theta = 90^o$ the $[\theta/0/-\theta/0]_s$ laminates correspond to a crossply composite (CPC).

2.0 RESULTS AND DISCUSSION

The predicted ply hygro transverse and intralaminar shear stresses for the three moisture profiles (linear, parabolic, and hyperbolic) and for the two different generic laminate configurations $[(\pm\theta)_2]_s$ and $[\theta/0/-\theta/0]_s$ are presented and discussed below. Longitudinal stresses are not presented since they are only about 10 percent of the corresponding ply strength.

2.1 LINEAR MOISTURE PROFILES

The ply transverse hygro stress in $[(\pm\theta)_2]_s$ composite laminates is plotted versus ply angle θ in figure 2. The moisture content in each ply is shown on the corresponding curve. The points to be noted in this figure are: (1) the transverse stress in the exposed ply (ply 1) is compression, is about 20 ksi and is insensitive to the ply angle; (2) the transverse stress in the protected ply (ply 8) is tensile and reaches a maximum magnitude of about 20 ksi at $\theta = 0$ and $\theta = 90^o$ (UDC) and a minimum magnitude (about 4 ksi) at $\theta = 45^o$ (CPC); (3) the distance between the curves for the different plies is about the same indicating that the ply transverse stress varies linearly through the thickness corresponding to the moisture profile; and (4) the curves are symmetric about $\theta = 45^o$ as expected.

Corresponding plots of the ply intralaminar shear stress are shown in figure 3. The points to be noted in this figure are: (1) the curves are antisymmetric about $\theta = 45^o$; (2) the ply intralaminar shear stress is maximum (5 ksi) in the protected ply (ply 8) at about $\theta = 30^o$; (3) the shear stress is negligible in the exposed ply (ply 1); and (4) the shear stress is zero at $\theta = 0$, 45^o and 90^o as expected.

The ply transverse hygro stress in $[\theta/0/-\theta/0]_s$ composite laminates is plotted versus ply angle θ in figure 4. The points to be noted in this figure are: (1) the transverse stress in the exposed ply (ply 1) is compression, reaches about 22 ksi at $\theta = 45^o$, and varies mildly with ply angle; (2) the transverse stress in the protected ply (ply 8) is tensile varying from about 20 ksi at $\theta = 0$ to about 4 ksi at $\theta = 90^o$. The corresponding intralaminar shear stresses are plotted in figure 5. As can be seen these stresses are relatively low (less than 4 ksi).

It is instructive to compare the maximum ply hygro stresses with corresponding ply strengths. The ply transverse and intralaminar shear strengths at about 1 percent moisture and room temperature are approximately the same as those reported at room temperature and 50 percent relative humidity (ambient conditions). The values of interest for these comparisons are from ref. 1: 30 ksi transverse compression, 9 ksi for transverse tension, and 9 ksi for intra-

laminar shear strength. Compared to these values, the ply transverse hygro compressive stress is about 24 ksi or 75 percent of the corresponding strength, the hygro transverse tensile stress is about 20 ksi ($\theta = 0$) or two times greater than the corresponding strength, indicating that transply cracking would occur in the protected ply. The transverse tensile stress at $\theta = 45^o$ (CPC) is about 4 ksi or about 45 percent of the ply strength. The hygro intralaminar shear stress is about 5 ksi or about 55 percent of the corresponding strength.

The conclusion from the above discussion is that linear moisture profiles, varying from 1 percent at the exposed ply to zero percent at the protected ply, in $[(\pm\theta)_2]_s$ or $[\theta/0/-\theta/0]_s$ composite laminates reach sufficiently high magnitudes to cause transply cracking in the protected ply.

2.2 PARABOLIC MOISTURE PROFILES

The ply transverse hygro stress in $[(\pm\theta)]_s$ composite laminates is plotted versus ply angle (θ) in figure 6. The moisture content in each ply is shown on the corresponding curve. As can be seen in figure 6, the transverse stress in the exposed ply (ply 1) is compression about 23 ksi at $\theta = 0$ and 90^o. The transverse stress decreases in magnitude progressively with ply number, changes to tension at about ply 5 and reaches a maximum tensile value of 17 ksi in the protected ply (ply 8) at $\theta = 0$ and 90^o. The transverse stress is relatively insensitive with θ up to ply 5. The greatest sensitivity of the transverse stress with θ is in ply 8 varying from 17 ksi at $\theta = 0$, to about 3 ksi at $\theta = 45^o$ and then back to 17 ksi at $\theta = 90^o$. The curves in figure 5 are symmetric with respect to $\theta = 45^o$.

The corresponding plots for the ply intralaminar shear stress in $[(\pm\theta)_2]_s$ composite laminates are shown in figure 7. The points to be noted in this figure are: (1) the intralaminar shear stress is maximum (about 4 ksi) in the protected ply at about $\theta = 30^o$ and decreases progressively in magnitude approaching negligible values at the exposed ply; and (2) the intralaminar shear stress is antisymmetric with respect to $\theta = 45^o$ and has zero magnitude at $\theta = 0$, 45^o and 90^o.

The ply transverse hygro stress in $[\theta/0/-\theta/0]_s$ composite laminates is plotted versus ply angle (θ) in figure 8. The points to be noted in this figure are: (1) the transverse stress in the exposed ply (ply 1) is compression and is about 23 ksi and is independent of θ; (2) the transverse stress is tension in the protected ply (ply 8) varying from about 16 ksi at $\theta = 0$ to about 3 ksi at $\theta = 90^o$; (3) the transverse stress in the other plies lies between these values changing from compression to tension between plies 4 and 5, and (4) the transverse stress with respect to θ is essentially insensitive when the stress is compression (plies 1 to 4) but is sensitive when the transverse stress is tension (plies 5 to 8).

The corresponding plots for the intralaminar shear stress in $[\theta/0/-\theta/0]_s$ composite laminates are shown in figure 9. (1) The shear stress is maximum in the protected ply, has a magnitude of about 4 kis at about $\theta = 30^o$, and and is zero at $\theta = 0$ and 90^o. The maximum intralaminar shear stress is less than 2.5 ksi in ply 6 and negligible in plies 3 and 1.

Both transverse and intralaminar shear hygro stresses vary approximately

parabolically through the ply thickness in both $[(\pm\theta)_2]_s$ and $[\theta/0/-\theta/0]_s$ composite laminates. To establish this variation it is necessary to show that the second difference between the stresses in consecutive plies remains constant at anyone ply angle in figures 6 and 8. This can easily be done but the details are not included herein. Plotting of the stress versus ply indicates that the parabolic variation of the stresses through the laminate thickness is not as severe as the corresponding moisture variation.

As was the case with the linear moisture profile, the ply transverse tensile hygro stresses are quite large (about 20 ksi) compared to corresponding ply strength (about 9 ksi) while the intralaminar shear stresses are relatively small (4 ksi compared to 9 ksi). Thus, transply cracking in the protected ply can also be caused by a parabolic moisture profile.

2.3 HYPERBOLIC MOISTURE PROFILE

The ply transverse hygro stress in $[(\pm\theta)_2]_s$ composite laminates is plotted versus ply angle (θ) in figure 10. The moisture content in each ply is given on the corresponding curve in the figure. The points to be noted in figure 10 are: (1) the maximum compressive transverse stress is in the exposed ply (ply 1) and is about 24 ksi at $\theta = 0$ and 90°; (2) the maximum tensile transverse stress is in the protected ply (ply 8) and varies from 13 ksi at $\theta = 0$ to 4 ksi at $\theta = 45^\circ$ back to $\theta = 90^\circ$; (3) the stress variation with θ is negligible in plies 1 through 4 and it is considerable in plies 5 through 8; (4) the stress curves are symmetric with respect to $\theta = 45^\circ$; and (5) the stress in ply 8 is the same as for the parabolic distribution while in the other plies the stress curves have the same shape but smaller magnitudes.

The ply transverse hygro stress in $[\theta/0/-\theta/0]_s$ composite laminates is plotted versus ply angle (θ) in figure 12. The points to be noted from this figure are: (1) the maximum compressive transverse stress is in the exposed ply (ply 1) and is about 24 ksi and is relatively insensitive to θ; (2) the maximum tensile transverse stress is in the protected ply (ply 8) varying from about 13 ksi at $\theta = 0$ to 3 ksi at $\theta = 90^\circ$; (3) the stresses in plies 1, 2, and 3 have negligible variation with θ while the stress variation with θ in the remaining plies is considerable; and (4) the curves in figure 12 are comparable to those for the parabolic moisture profile (fig. 8).

The corresponding plots for the intralaminar shear stress in $[\theta/0/-\theta/0]_s$ composite laminates is shown in figure 13. As can be seen in this figure, the shear stress is relatively small (less than 2 ksi).

The significant observations from the above discussion are: (1) the transverse tensile hygro stress in $[(\pm\theta)_2]_s$ and $[\theta/0/-\theta/0]_s$ composite laminates can reach relatively high magnitudes, 13 to 16 ksi, compared to 9 ksi for the corresponding ply strength; (2) the intralaminar shear stress is about 2 ksi which is relatively small compared to 9 ksi for the corresponding ply strength; and (3) the hyperbolic and parabolic moisture profiles result in about the same ply stresses.

2.4 COMPARISON OF MAXIMUM PLY STRESSES FOR THE THREE MOISTURE PROFILES

The maximum ply transverse compression, maximum transverse tension

($\theta = 0$, 45° or 90°) and intralaminar shear hygro stresses, including corresponding ply strengths, are summarized in table I for comparison purposes. The points to be noted from table I are: (1) the maximum transverse compressive stress occurs in the exposed ply and is not very sensitive to either moisture profile or laminate configuration; (2) the maximum transverse tensile stress occurs in the protected ply and is sensitive to both moisture profile and to laminate configuration; (3) the maximum intralaminar shear stress is insensitive to both moisture profile and laminate configuration; and (4) as was previously stated, the maximum transverse compression stress is about 70 to 80 percent of the corresponding ply strength; the maximum transverse tensile is about 140 to 220 percent greater at $\theta = 0$, indicating that transply cracks would occur but is only 33 to 44 percent for $\theta = 45^{\circ}$ or 90°; and the maximum intralaminar shear stress is about 20 to 55 percent of the corresponding ply strength.

The conclusions from the previous discussion are: (1) the maximum ply transverse compression hygro stress is not sensitive to either moisture profile or laminate configuration; (2) the maximum ply transverse tensile hygro stresses are sensitive to both moisture profile and laminate configuration, and can reach sufficiently high magnitudes to cause transply cracks; (3) the ply intralaminar shear stresses are sensitive to both moisture profile and laminate configuration but their magnitudes are low compared to ply strength; and (4) the maximum transverse stresses occur in unidirectional laminates when subject to moisture profiles, whereas the maximum intralaminar shear stresses occur in $[(\pm 30)_2]_s$ laminates.

2.5 IMPLICATIONS FOR DESIGN PURPOSES

The most important implication of this analysis is that the designer should make every effort to avoid or minimize moisture gradients through the laminate thickness, especially when unidirectional composites are involved. Hygro stresses resulting from a 1 percent moisture gradient can significantly reduce the residual strength of a laminated composite and may cause cracking of the protected ply.

If moisture gradients cannot be avoided, they should certainly be accounted for in an analysis. If the actual moisture gradient profile is unknown, the assumption of a linear gradient will yield conservative predictions of the transverse tensile and intralaminar shear hygro stresses. Note that the hygro stresses are in addition to any residual stresses that may be present.

3.0 SUMMARY OF RESULTS AND CONCLUSIONS

A computational investigation was performed using a recently developed integrated hygrothermomechanical theory to predict the effects of three different moisture profiles (linear, parabolic and hyperbolic varying from 1 percent moisture in the exposed ply to zero in the protected ply) on hygro stresses in two generic $[(\pm\theta)_2]_s$ and $[\theta/0/-\theta/0]_s$ ($0 \leq \theta \leq 90$) intermediate modulus graphite fiber reinforced epoxy resin (AS/E) composite laminates. The significant results and conclusions of this investigation are summarized below.

(1) The maximum ply transverse tensile hygro stress is sensitive to both moisture profile and laminate configuration and it can reach magnitudes sufficiently high (220 percent of the cor-

responding ply strength) to cause transply cracking in the plies near and at the protected surface.

(2) The maximum ply transverse compressive hygro stress occurs in the exposed ply. It is not sensitive to either moisture profile or laminate configuration and can reach a magnitude of about 80 percent of the corresponding ply strength.

(3) The maximum ply intralaminar shear hygro stress is sensitive to both moisture profile and laminate configuration. It can reach magnitudes of about 55 percent of the corresponding ply strength in the plies close to the protected surface.

(4) The maximum transverse stress occurs in a unidirectional laminate while the maximum intralaminar shear stress occurs in the $[(\pm 30)_2]_s$ laminate.

(5) The assumption of a linear moisture profile would lead to a conservative prediction of the ply transverse tensile hygro stresses.

4.0 REFERENCES

1. Chamis, C. C., Lark, R. F., and Sinclair, J. H., "An Integrated Theory Predicting the Hydrothermomechanical Response of Advanced Composite Structural Components," NASA TM-73812, 1977.

5.0 BIOGRAPHIES

C. C. CHAMIS

Dr. Chamis is presently with the Structures Section of the NASA-Lewis Research Center, Cleveland, Ohio, where he has been since 1968. He received his B. S. in Civil Engineering (1960) from Cleveland State, M. S. (1962), and Ph. D. (1967) in Engineering Mechanics from Case Western Reserve University where he was a member of the Engineering Design Center. His current research is in the area of analysis, design and optimization of composite structural components. He is also involved in the analysis and design of test methods for advanced composites. His experience in structural fiber composites dates back to 1962 when he was with the Engineering Analysis group of B. F. Goodrich Research Center. Dr. Chamis has authored and coauthored numerous articles covering all aspects of composite mechanics and structures.

J. H. SINCLAIR

J. H. Sinclair received a B. S. Degree from Michigan State University. He has been a member of the Materials and Structures Division at the NASA-Lewis ResearchCenter since 1956. He is presently with the Composites and Structures Branch and is involved with the testing of composites for the purpose of characterization and the identification of failure modes. He has also performed finite element analysis of complex composite structures including composite laminates, composite blades, and strip hybrids.

R. F. LARK

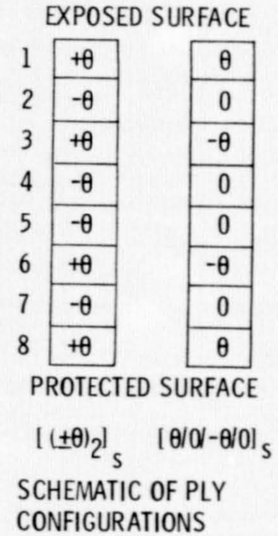
Mr. Lark is assigned to the Structures Section, Composites and Structures Branch of the NASA-Lewis Research Center, Cleveland, Ohio, where he has been since 1958. He received his B. S. in Chemical Engineering (1948) from Case Institute of Technology. His current work assignment involves the project management of in-house and contractual programs for the development

of composite pressure vessels and composite materials for aircraft engine components. Other experience includes the development of positive expulsion devices, advanced fibers, resins and adhesives. He has contributed significantly to the advancement of the state-of-the-art of composite pressure vessels and positive expulsion technology and advanced composites in general.

TABLE I. - SUMMARY OF MAXIMUM PLY STRESSES DUE TO THREE MOISTURE PROFILES IN TWO AS/E COMPOSITE LAMINATES AND COMPARISONS WITH PLY STRENGTHS

Laminate configuration/ moisture profile		Stress (ksi) in				
		Exposed ply		Protected ply		
		Transverse	Intralaminate shear	Transverse		Intralaminar shear
$[(\pm\theta)_2]_s$	Linear	-22 (0)[a]	~0	20 (0)	4 (45)	5 (30)
	Parabolic	-23 (0)	~0	17 (0)	3 (45)	4 (30)
	Hyperbolic	-24 (0)	~0	13 (0)	4 (45)	3 (30)
$[\theta/0/-\theta/0]_s$	Linear	-22 (45)	~0	20 (0)	4 (90)	4 (30)
	Parabolic	-23 (0)	~0	16 (0)	3 (90)	3 (30)
	Hyperbolic	-24 (0)	~0	13 (0)	3 (90)	2 (30)
Ply strengths (ref. 1)		-30	9	9	9	9

[a]Number in parentheses indicates the ply angle at which the value occurred.



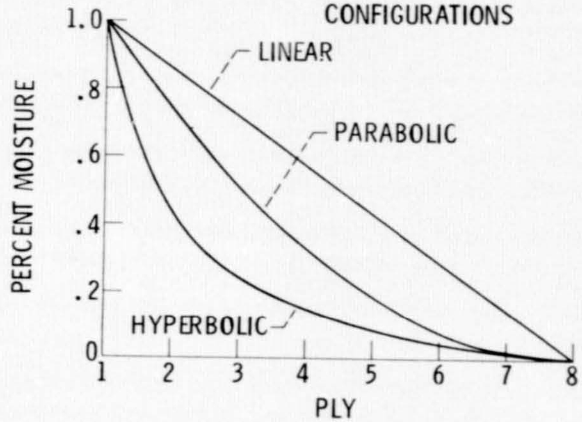


Figure 1. - Moisture profiles through the laminates.

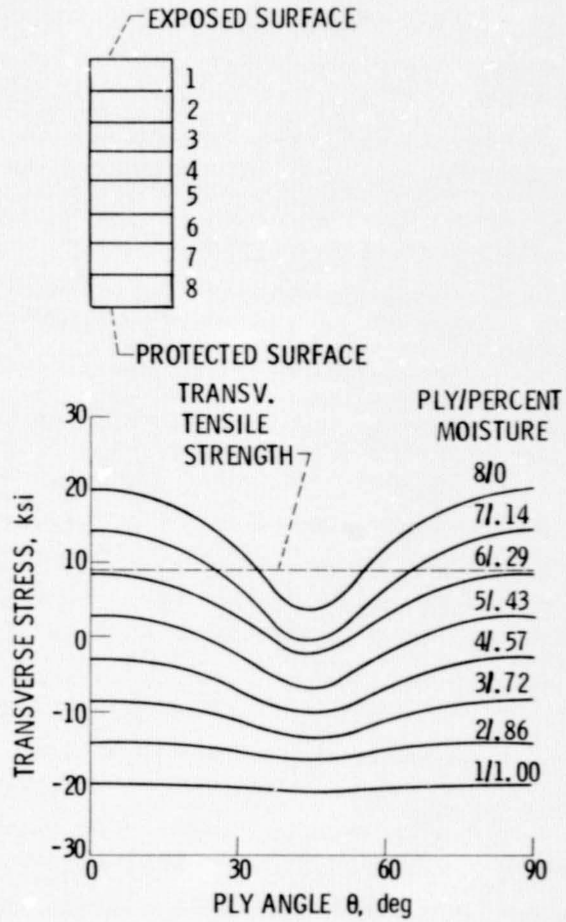


Figure 2. - Ply transverse hygro stresses in $[(\pm\theta)_2]_s$ AS/E composite laminates with one surface exposed and the other protected. Linear moisture profile.

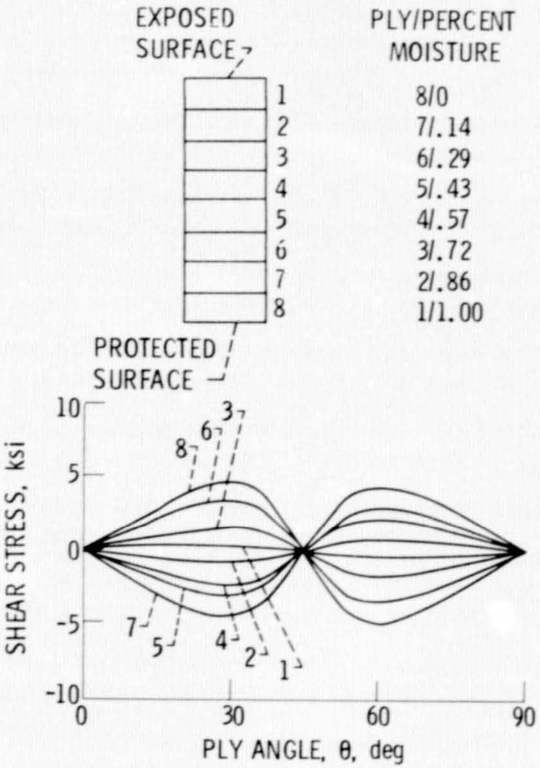


Figure 3. - Ply intralaminar shear hygro stresses in $[(\pm\theta)_2]_s$ AS/E composite laminates with one surface exposed and the other protected. Linear moisture profile.

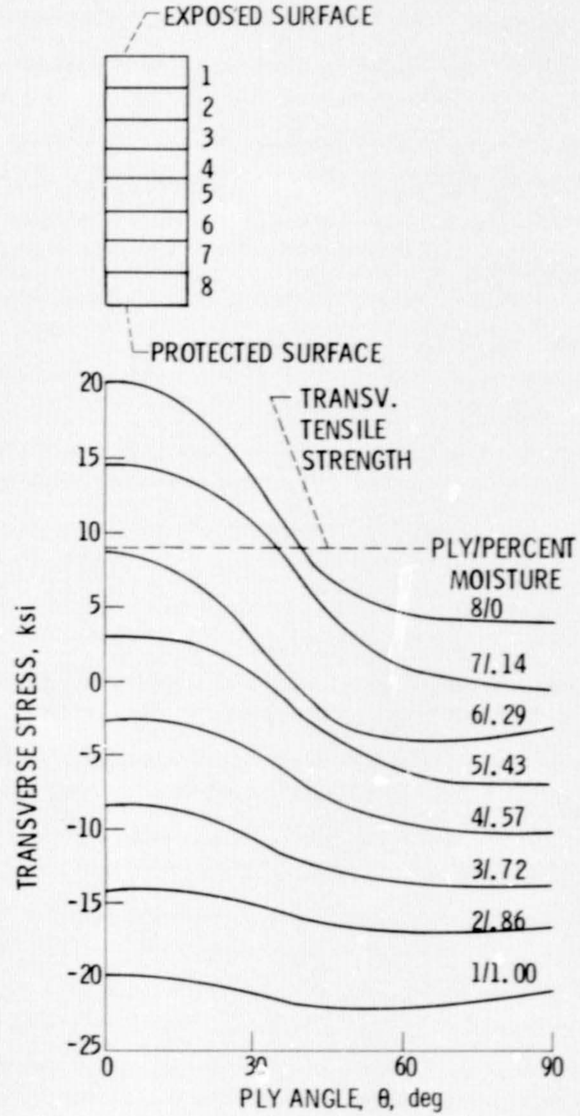


Figure 4. - Ply transverse hygro stresses in $[\theta/0/-\theta/0]_s$ AS/E composite laminates with one surface exposed and the other protected. Linear moisture profile.

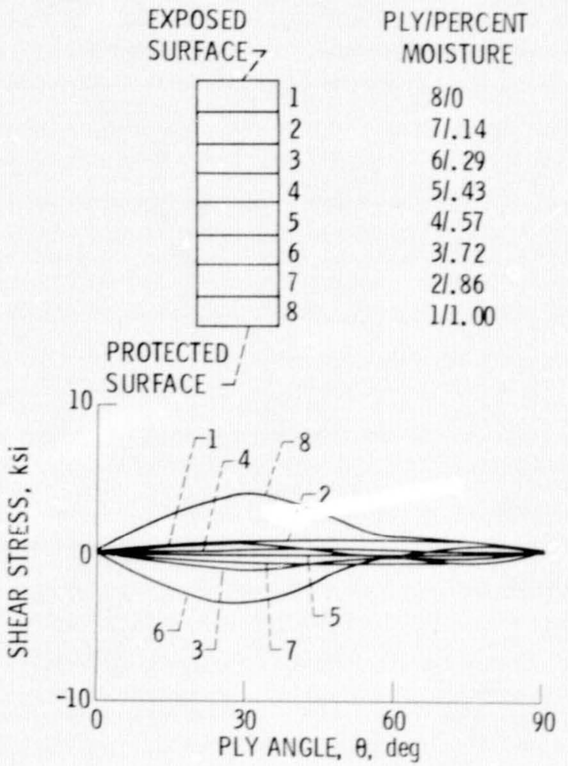


Figure 5. - Ply intralaminar shear hygro stresses in $[\theta/0/-\theta/0]_S$ AS/E composite laminates with one surface exposed and the other protected. Linear moisture profile.

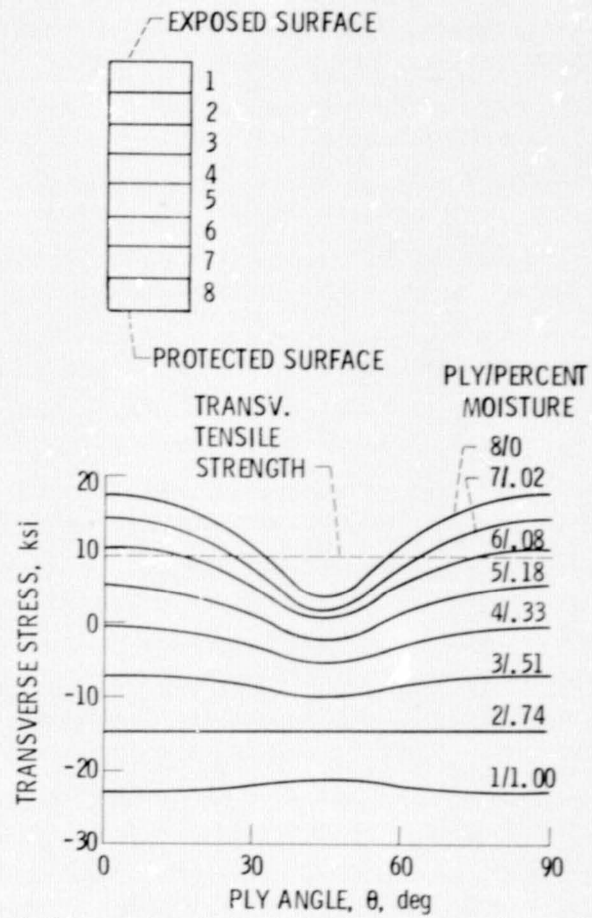


Figure 6. - Ply transverse hygro stresses in $[(\pm\theta)_2]_S$ AS/E composite laminates with one surface exposed and the other protected. Parabolic moisture profile.

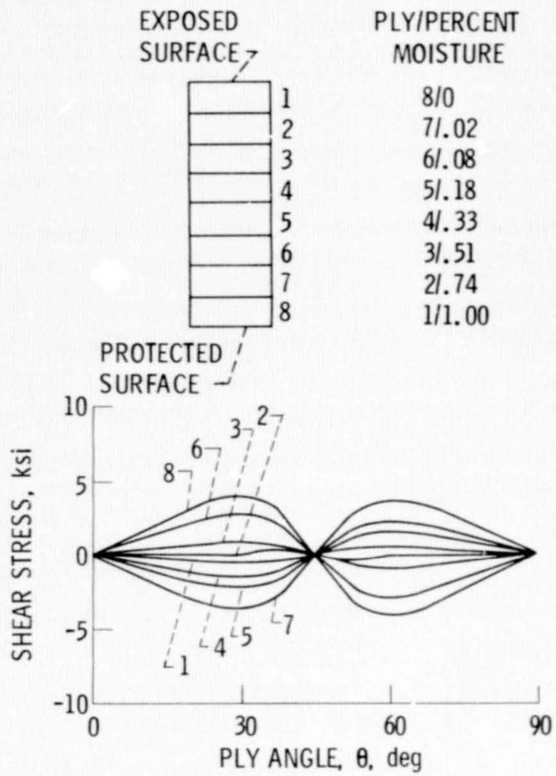


Figure 7. - Ply intralaminar shear hygro stresses in $[(\pm\theta)_2]_s$ AS/E composite laminates with one surface exposed and the other protected. Parabolic moisture profile.

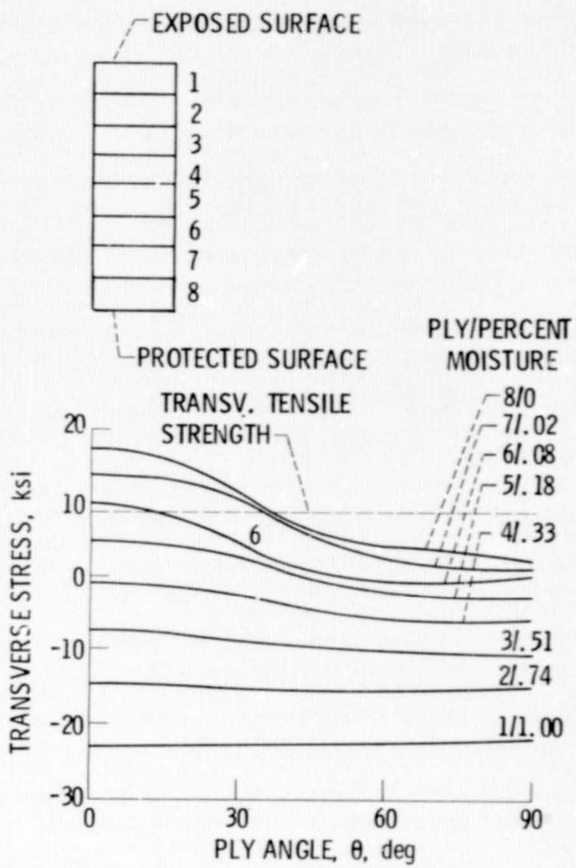


Figure 8. - Ply transverse hygro stresses in $[\theta/0/-\theta/0]_s$ AS/E composite laminates with one surface exposed and the other protected. Parabolic moisture profile.

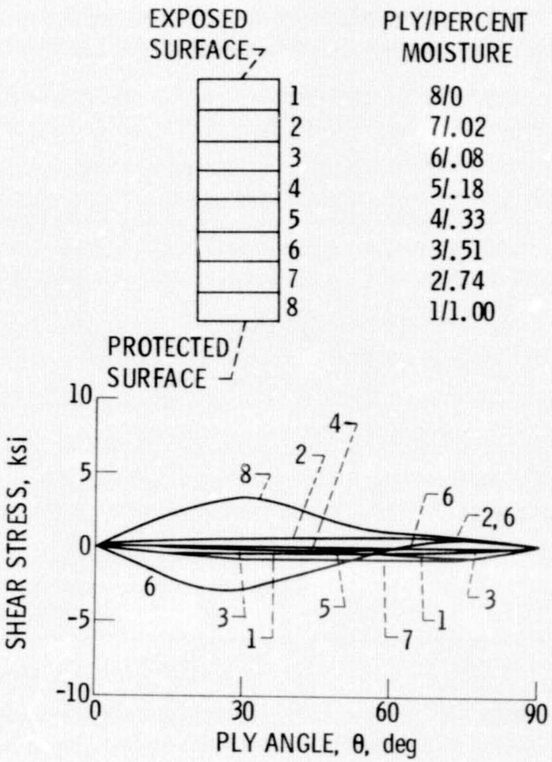


Figure 9. - Ply intralaminar shear hygro stresses in $[\theta/0/-\theta/0]_s$ AS/E composite laminates with one surface exposed and the other protected. Parabolic moisture profile.

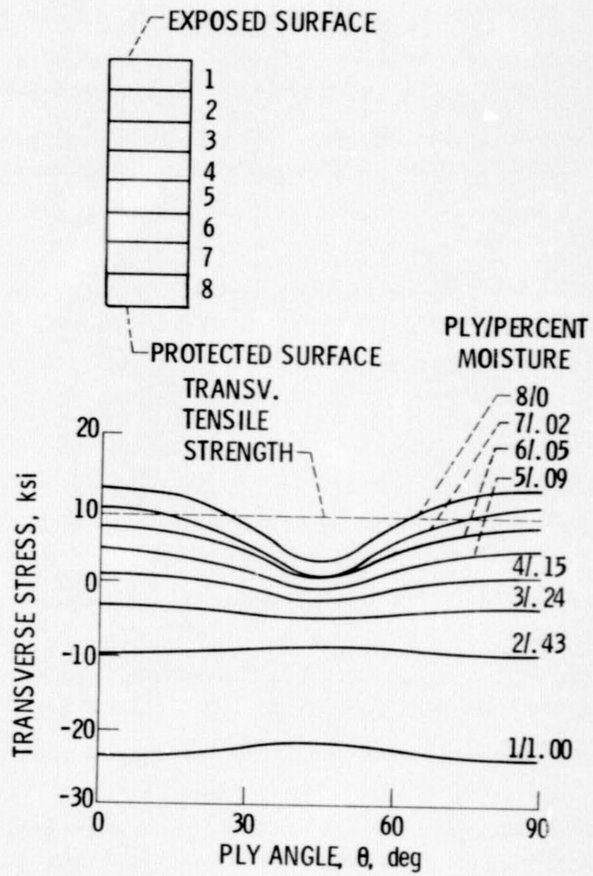


Figure 10. - Ply transverse hygro stresses in $[(\pm\theta)_2]_s$ AS/E composite laminates with one surface exposed and the other protected. Hyperbolic moisture profile.

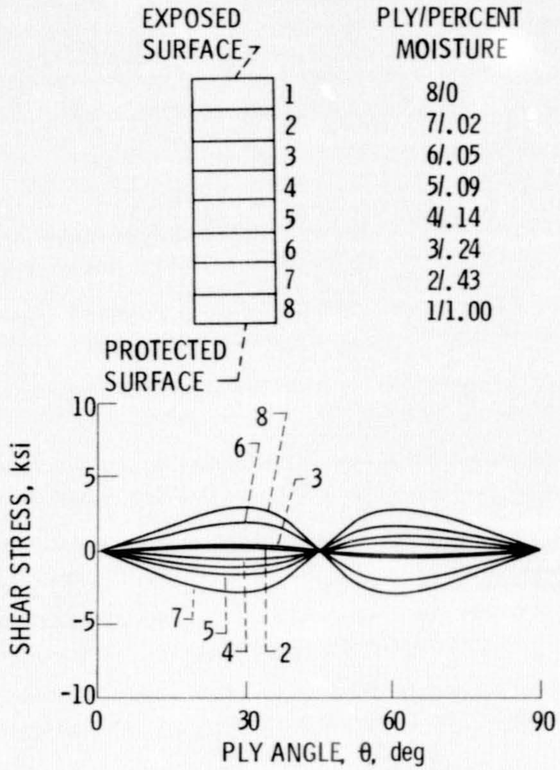


Figure 11. - Ply intralaminar shear hygro stresses in $[(\pm\theta)_2]_s$ AS/E composite laminates with one surface exposed and the other protected. Hyperbolic moisture profile.

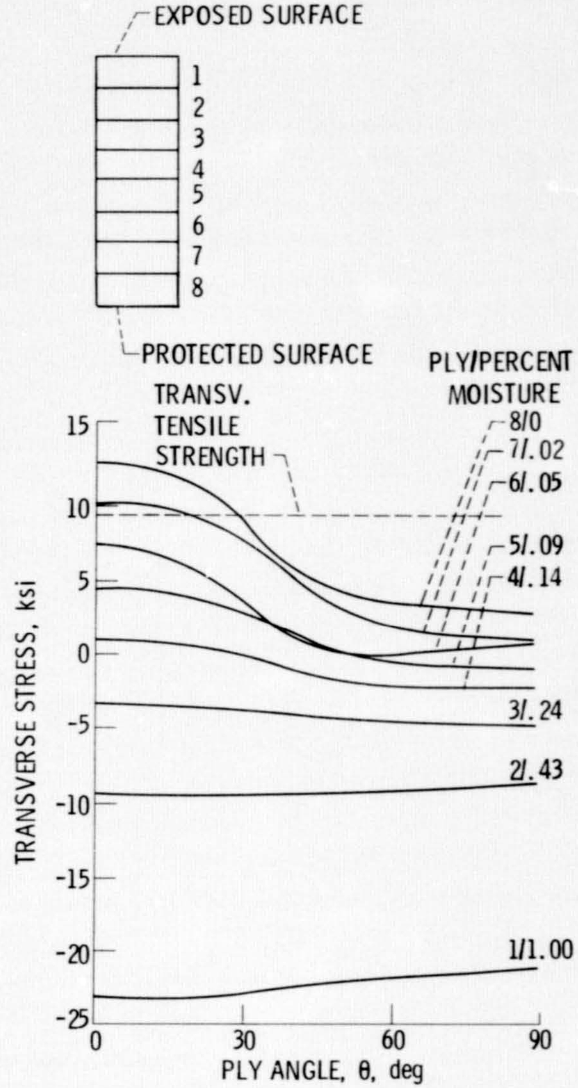


Figure 12. - Ply transverse hygro stresses in $[\theta/0/-\theta/0]_s$ AS/E composite laminates with one surface exposed and the other protected. Hyperbolic moisture profile.

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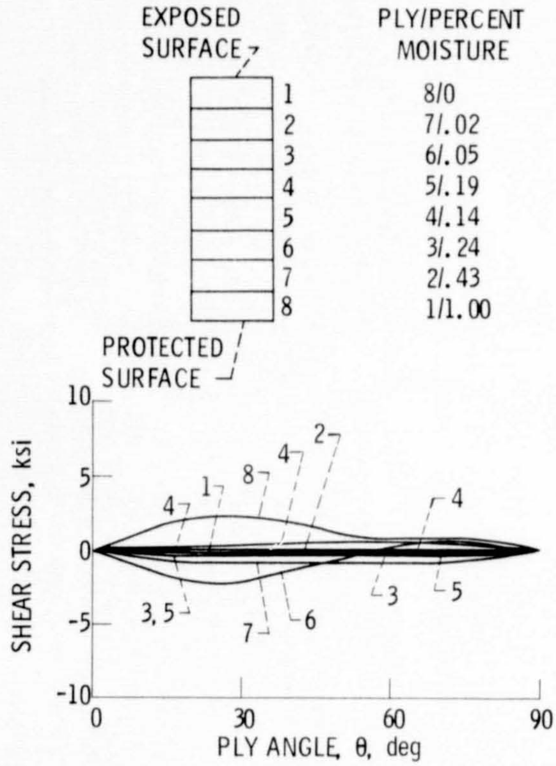

Figure 13. - Ply intralaminar shear hygro stresses in $[\theta/0/-\theta/0]_S$ AS/E composite laminates with one surface exposed and the other protected. Hyperbolic moisture profile.